

New Universality Class at the Magnetic Field Tuned Superconductor-Insulator Transition?

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The superconductor-insulator transition in ultrathin films of amorphous Bi was tuned by an applied magnetic field. A finite size scaling analysis has been carried out to determine the critical exponent product $\nu z = 0.7 \pm 0.1$ for five films of different thicknesses and normal state resistances. This result differs from the exponents found in previous experiments on InO_x and MoGe films. We discuss several possible reasons for this disagreement.

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The superconductor-insulator (SI) transition in two-dimensional disordered systems has been extensively studied theoretically in the context of the dirty boson model at zero temperature. Monte Carlo simulations [1,2] and renormalization group calculations [3] mostly focused on the case when the transition is tuned by changing the carrier concentration, coupling strength or the strength of the disorder. The SI transition can also be tuned by changing the external magnetic field [4]. Scaling arguments [5] give a lower bound on the correlation length exponent $\nu \geq 1$, and predict the value of the dynamical critical exponent to be $z=1$ [4,6]. An experimental scaling analysis of the magnetic field tuned SI transition has been carried out for thin films of InO_x [7] and MoGe [8]. Both experiments found $\nu z \approx 1.3$, consistent with the theoretical predictions. We have studied the magnetic field tuned SI transition in amorphous ultrathin homogeneous films of Bi. Finite size scaling analysis yields $\nu z \approx 0.7$ which is in disagreement with the predictions of Ref. [4], as well as with the results of Refs. [7] and [8].

The investigations were carried out on five ultrathin Bi films with thicknesses close to 12-13Å. The films were evaporated on top of a 10Å thick layer of amorphous Ge, which was pre-deposited onto a 0.75mm thick single-crystal of SrTiO_3 (100). The film thickness was systematically increased *in situ* under UHV conditions ($\sim 10^{-10}$ Torr), with the substrate temperature kept below 20 K during all depositions. Film thicknesses were determined using a previously calibrated quartz crystal monitor. Films prepared in this manner are believed to be homogeneous, since it has been found that they become connected at an average thickness on the order of one monolayer [9]. Between the successive depositions, resistance measurements were carried out using a stan-

dard dc four-probe technique with current bias up to 50nA. Magnetic fields up to 12kG perpendicular to the plane of the sample were applied using a superconducting split-coil magnet.

A typical temperature dependence of the resistance as the magnetic field changes is shown on Fig.1. In zero field, the resistance decreases with increasing temperature suggesting the existence of superconducting fluctuations. Magnetic field destroys this downward curvature, and at some critical magnetic field, B_c , the resistance is independent of temperature. In magnetic fields higher than B_c the film is insulating, with $\delta R/\delta T > 0$. The critical magnetic field is determined by plotting the resistance as a function of magnetic field for different temperatures (Inset of Fig.1) and identifying the crossing point for which the resistance is temperature independent, or by plotting dR/dT as a function of magnetic field at the lowest temperatures and finding the field for which $(dR/dT) = 0$ [7].

The scaling relation for the resistance of a two dimensional system close to the magnetic field tuned superconductor insulator transition was suggested by Fisher [4]:

$$R(\delta, T) = R_c f(\delta T^{-1/\nu z}) \quad (1)$$

Here $\delta = B - B_c$ is the deviation from the critical field, R_c is the critical resistance at $B = B_c$, $f(x)$ is a universal scaling function such that $f(0) = 1$, ν is the coherence length exponent, and z is the dynamical critical exponent. To carry out the analysis of the data, we introduce a parameter $t \equiv T^{-1/\nu z}$, and adjust $t(T)$ at each temperature so that all the resistance data collapse on a single curve. The critical exponent product νz is then found from the temperature dependence of t . This procedure does not require prior knowledge of the critical exponents or detailed knowledge of the functional form of the temperature or field dependence of the resistance.

The collapse of the resistance data as a function of δt for one of the samples is shown in Fig.2. The critical exponent product νz , determined from the temperature dependence of the parameter t (Inset of Fig.2), is found to be $\nu z = 0.7 \pm 0.1$. The same exponents were obtained using a somewhat different method of plotting $(dR/dB)|_{B_c}$ vs T^{-1} on a log-log plot and determining the slope which is equal to $1/\nu z$ [7]. The analysis was carried out for five films of different thicknesses, all yielding $\nu z = 0.7 \pm 0.1$, apparently independent of the film thickness. In fact,

plotting the normalized resistance R/R_c as a function of the scaling variable reveals that they all scale together (Fig. 3). This behavior strongly suggests that the scaling function is universal.

The critical resistance, however, does not seem to be universal. Figure 4 shows that R_c decreases as the critical field increases, roughly in a linear fashion. Very similar behavior was observed by Yazdani and Kapitulnik [8].

The critical exponent product νz found in this experiment does not agree with the theoretical prediction that $\nu \geq 1$ and $z = 1$ [4] for a disordered system, nor with the experimentally obtained $z = 1$ and $\nu \approx 1.3$ for a magnetic field tuned SI transition in thin films of amorphous InO_x [7] and MoGe [8]. There could be a number of possible reasons for this disagreement, which we discuss next.

The prediction that $\nu \geq 1$ follows from an exact theorem [10] which is expected to hold for any transition which can be tuned by changing the strength of the disorder. It has been argued recently [11] that this is not necessarily the case, and that the disorder averaging may play an important role in determining the critical exponents. The nature of disorder would be crucial here.

Without disorder, the SI transition in a 2D system might belong to the universality class of the classical 3D XY model [4,6]. The exponent product we find for the field-driven transition is very close to that obtained for the classical 3D XY model. Numerical simulations of a $T=0$ critical point for the boson Hubbard model in 2D for which there is no disorder [2] also find $\nu z \approx 0.7$. Since our films are believed to be very homogeneous, it is possible that the length scale which characterizes the disorder is very small compared to the diverging coherence length, and the system behaves as if there were no disorder.

The importance of the length scale and the nature of disorder might also explain the difference between our results and those of Refs. [7] and [8]. Since both InO_x and MoGe are composite materials, the length scale for disorder might be quite different from that of monoatomic amorphous Bi. Indeed, InO_x films in a magnetic field appear to be in a quasi-reentrant regime, suggestive of the behavior of granular films in zero field [12]. Second, the way the samples are prepared might result in a profoundly different nature of the disorder. In InO_x and MoGe, the normal state resistance is determined by the composition (content of oxygen and germanium, respectively), while in quench condensed Bi films it depends on the film thickness. We also wish to point out that the Bi films used in this study are almost an order of magnitude thinner than the samples of Refs. [7] and [8].

It has been suggested that a local dissipation for the phase of the superconducting order parameter due to gapless electronic excitations might change the universality class of the system and lead to a non-universal critical resistance [13]. The critical resistance is expected to increase with increasing damping due to dissipation, which

might be expected to increase with decreasing normal state resistance. We however observe that the critical resistance decreases as the normal state resistance goes down, which is exactly the opposite of the behavior predicted by Ref. [13].

A recent work by Shimshoni et al. [14] considers the system close to the SI transition to be a binary composite of an insulating and a superconducting phase. Using incoherent Boltzman transport theory, they derive resistivity laws in different temperature regimes and predict finite dissipation at $T=0$ at all fields. We do not observe any saturation in the temperature dependence of the resistance as the temperature decreases ($\delta R/\delta T$ is non-zero down to the lowest temperatures). A satisfactory fit to the predicted resistivity laws also could not be obtained.

Local fluctuations of the amplitude of the superconducting order parameter are usually neglected in the scaling theory and the numerical simulations, but might actually be important. It has been suggested that the percolation of islands with strong amplitude fluctuations might mask the localization exponents obtained from the scaling theory [15].

The existence of electronic excitations was also used to explain the non-universal behavior of the critical resistance in Ref. [8]. A model of two-channel conduction was proposed, where the conductance due to the electron channel adds to the conductance due to the boson channel. Films with lower normal state resistances would have lower critical resistances due to a larger fraction of normal electrons. Our data could only be explained this way if the quantum resistance due to pairs were *greater* than $h/4e^2$. The conductance due to the electronic channel in a magnetic field might also depend on the strength of the spin-orbit interactions, which is another major difference between our samples and those of Refs. [7] and [8]. There is, however, a striking similarity in the magnetic field and normal state resistance behavior of the critical resistance.

We should note that the critical resistance is predicted to be universal only at $T=0$, while the finite temperature corrections are expected to be scaled by T_c [4]. Normal state resistances of the MoGe films of Ref. [8] are a factor of 3-10 lower than the Bi films considered here, and are far away from the critical point of the disorder driven transition. This means that our samples are probing a different part of the phase diagram [4,16], and the finite temperature corrections might be more important in one case than the other. There is also a question of whether any of the experiments really accessed the quantum critical region [17].

In order to resolve some of the issues discussed in this paper, simulations in which the magnetic field is the tuning parameter would be very useful.

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FIG. 1. Resistance per square as a function of temperature in different magnetic fields, ranging from 0kG (bottom) to 12kG (top), with 1kG increments. Inset: Resistance per square as a function of magnetic field at 0.15, 0.17, 0.19, 0.2, 0.25, 0.3 and 0.35K.

FIG. 2. Resistance per square as a function of the scaling variable, $t|B - B_c|$, for seventeen different temperatures, ranging from 0.14K to 0.5K. Here $t = T^{-1/\nu z}$ is treated as an adjustable parameter to obtain the best collapse of the data. Different symbols represent different temperatures. Inset: Fitting the temperature dependence of the parameter t to a power law determines the value of νz .

FIG. 3. Normalized resistance per square as a function of the scaling variable, $T^{-1/\nu z}|B - B_c|$, at 0.15K for five films: 12.239Å (squares), 12.353Å (diamonds), 12.455Å (crosses), 12.553Å (triangles) and 12.660Å (circles). Only one temperature was shown for each film for clarity.

FIG. 4. The critical resistance as a function of the critical field for the same five films of Fig.3. Here R_c decreases with increasing thickness, as thicker films have lower normal state resistances and higher critical fields.







